Activities at the CSNR for the NTR, Mars Hopper and a Mars Sample Return

Dr. Steven D. Howe
Center Director

Nuclear technologies in space require launching radioactive sources

- **Fission Surface Power (FSP) – deemed ENABLING by the NASA Mars Architecture Team (2008)**
- **Multi Mission Radioisotope Thermoelectric Generators (MMRTG) and Advanced Stirling Radioisotopic Generator (ASRG) are ENABLING for all long duration missions beyond Mars**
- **Nuclear Thermal Rockets (NTR) – deemed the PREFERRED technology by the Mars Architecture Team for the human mission**

A Universal Encapsulation method that is qualified for launch allows all of these applications

Today's Topics

- Universal encapsulation of radioisotopes
- Mars Hopper
- Nuclear Thermal Rocket (NTR)
- NTR Driven Mars Sample Return Mission
- Student programs at the CSNR

Universal Encapsulation - Common technology for reactor fuels and radioisotope sources

- **The distribution and encapsulation of radioisotope materials and nuclear fuels in an inert carrier matrix will address several issues and requirements for space power applications:**
  - Potential to address non-proliferation security requirements.
  - The ability to survive re-entry into Earth's atmosphere and impact under accident conditions.
  - Assembly & handling safety
  - Reduction in material self interaction such as α-n reactions.
  - Self-shielding properties.
- **The SPS acquired with a INL LDRD grant enables fabrication of tungsten parts at nearly full theoretical density**

Tungsten Cermet Fuels

- Ceramic-Metallic (cermet) matrix composed of ceramic fuel (UO_2 or UN) and tungsten alloy carrier
- Provide mechanical retention of nuclear fuels and fission products
- Provide good thermal conduction paths to coolant or propellant (NTR)
- Provide resistance to hot-hydrogen erosion and embrittlement.
- High melting temperature temperature (3422ºC)
  - high operational temperatures
  - resistance to atmospheric re-entry
- Investigated under 710-Program (Hot pressed)
  - - Fabrication process crucial to production success

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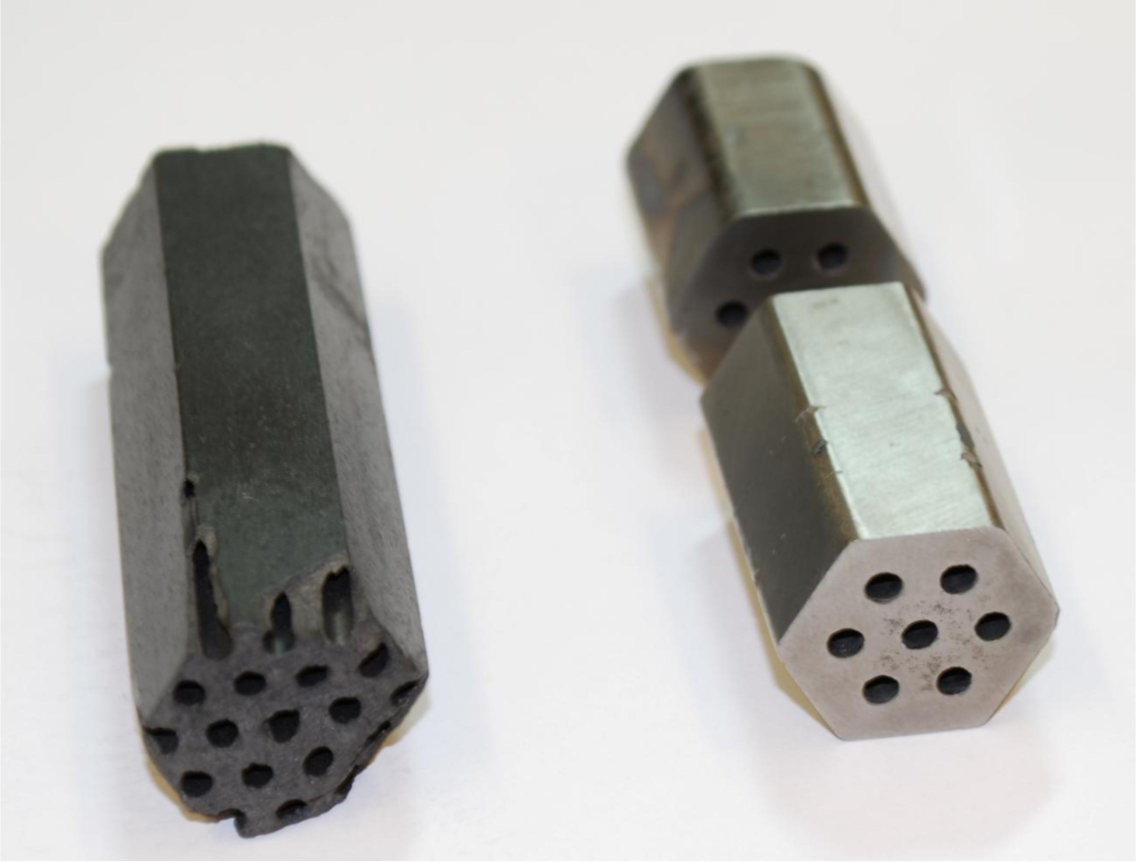
Fuel Element production by SPS

- (Left) NERVA graphite fuel element
- (Right) Leicester / CSNR tungsten fuel elements upon removal from die (no machining required)



Several applications will benefit from a qualified Universal Encapsulation

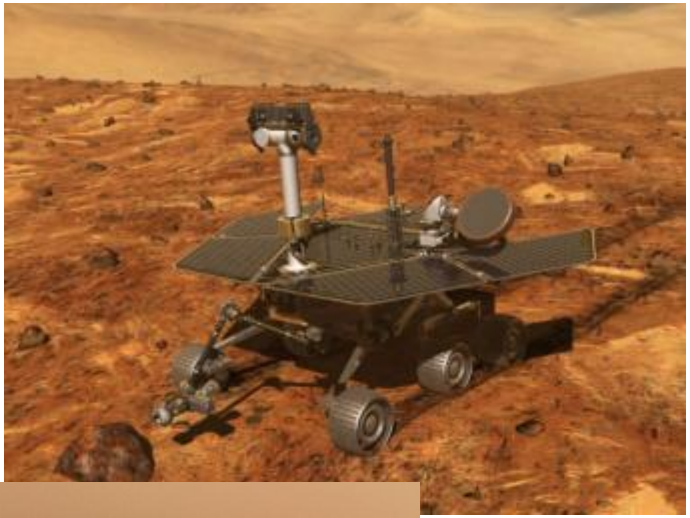
- **Advanced radioisotope sources**
- **Mars Hopper**
- **Nuclear Thermal Rocket**
- **Nuclear surface reactor**

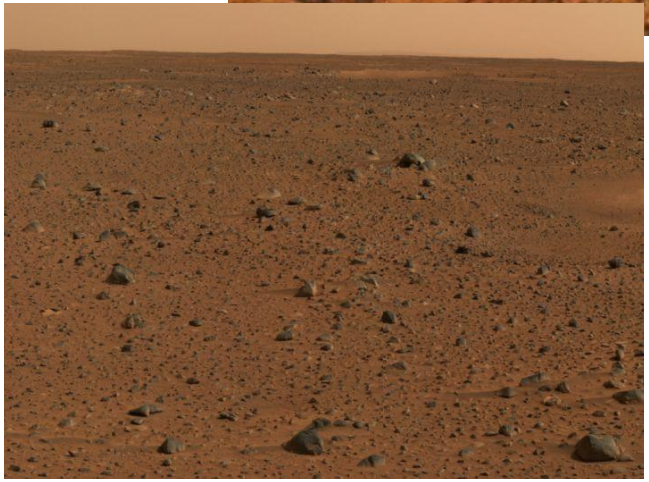
Mars Hopper:
A radioisotope powered, long-lived, long-range mobile platform using in-situ resources

Initiated in the 2009 CSNR Summer Fellows program

Planetary exploration is getting tougher

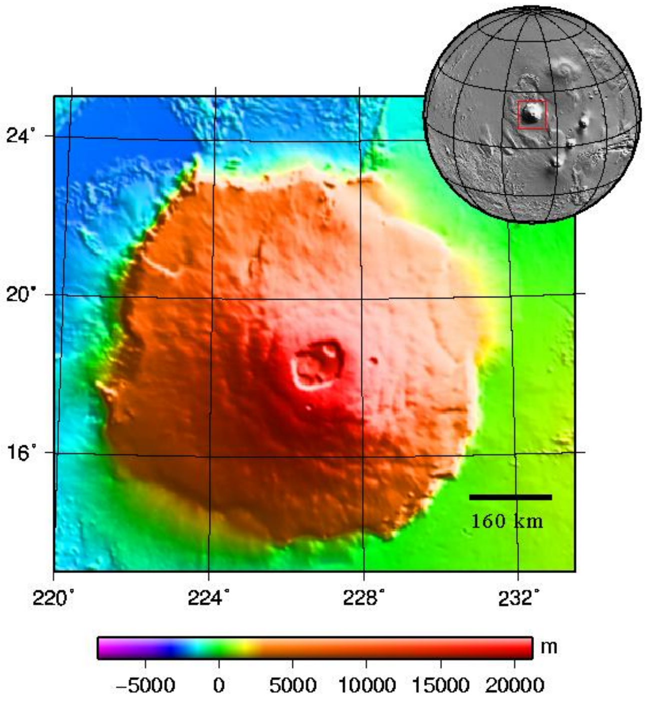
- **Planetary exploration is getting expensive**
- **Orbital good but still don't know subsurface constituency or water to high resolution**
- **MERs did great but only 15 km total after 5 years**
- **Surface landings necessitate flat, safe landing site**
- **Need more science per $**

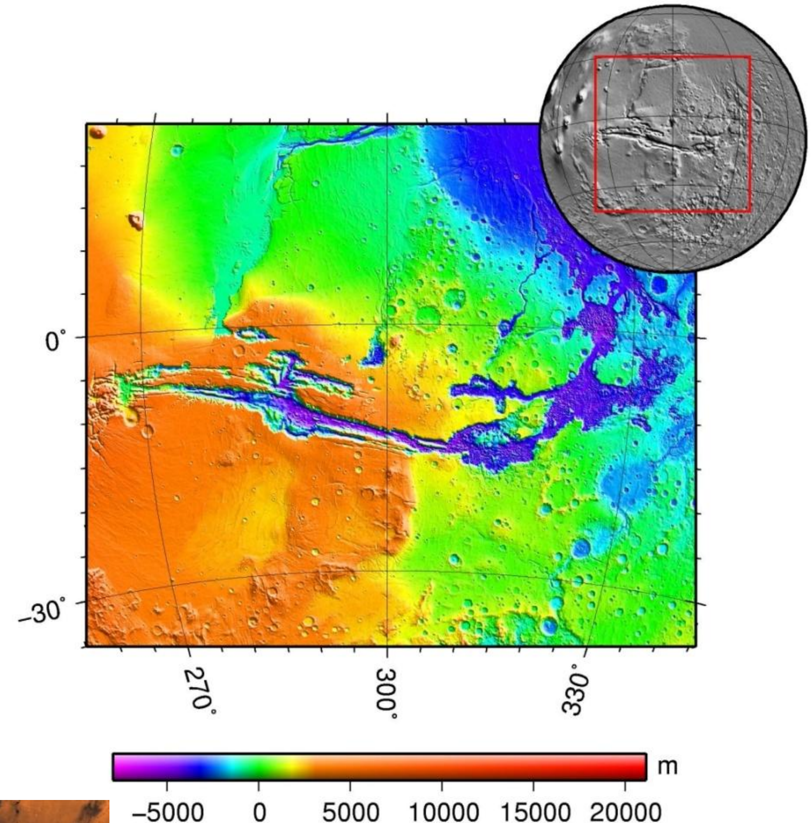




Interest in canyon walls, mountainsides, deep canyon bottoms

Olympus Mons





Valles Marineris

Ultimate goal is the Mars Sample Return

- **High priority mission**
- **Difficult to accomplish due to ascent/descent requirements**
- **Conflict between safe landing site and getting samples from interesting regions**
- **Desire many samples from all over the planet**
- **Requires a long lived, highly mobile craft to acquire samples and accumulate them at a centralized location**

Revolutionizing Planetary Exploration – the Mars Hopper

- **Concept:**
  - Utilize a Radioisotope Thermal Rocket (RTR) to store energy and “hop” a vehicle across the Martian surface

- **Enables:**
  - Science data collection from several regions and potentially a sample return mission
  - Could cover “pole-to-pole” in three years
  - Dozens of small platforms can be delivered due to small size for a meteorology network

Concept

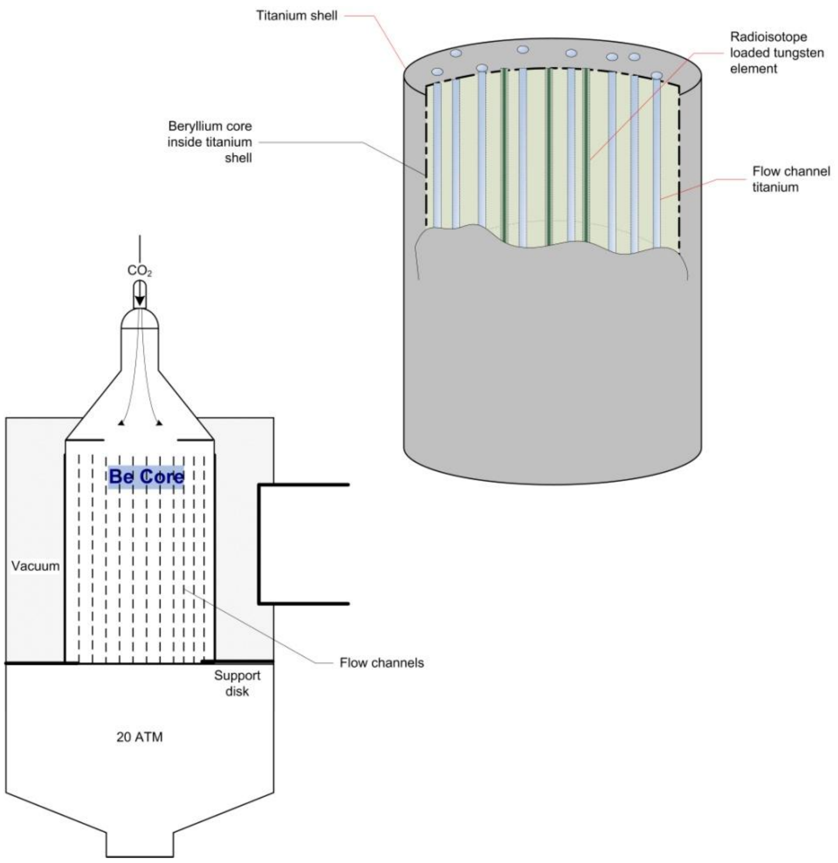
- The Mars Hopper concept utilizes energy from radioisotopic decay in a manner different from any existing RTGs, i.e. as a thermal capacitor.
  - Radioisotope sources have very high specific energy, j/kg, while having rather low specific power, w/kg.
    - Pu-238 has a specific energy of 1.6×10^6 MJ/kg which is 160,000 times the specific energy of chemical explosives.
    - Factoring in the 25% conversion to electricity, the system may have 4×10^5 MJ/kg of electrical energy compared to the 0.72 MJ/kg for Li-ion batteries.
  - By accumulating the heat from radioisotopic decay for long periods, the power of the source can be dramatically increased for short periods.

Concept

- **The basis for the concept is to utilize the decay heat from radioactive isotopes to heat a block of material to high temperatures.**
  - While the heating is taking place, some of the thermal power is diverted to run a cryocooler.
  - The cryocooler takes in the Martian atmosphere and liquefies it at 3 MPa.
  - Once the tank full, the power convertor is turned off and the core is allowed to increase in temperature.
  - After a peak temperature of 1200 K is reached, the liquid CO2 is injected into the core, heated, expanded through a nozzle, and allowed to produce thrust.
  - Part of the CO2 propellant is “burned” for ascent. After a ballistic coast, the remaining propellant is used for a soft landing.
  - Once landed, the process repeats.

Core subsystem -- Thermal issues

- Separate heating from cooling geometries
- Allow radiative losses only
- Utilize radiative loss as source for power conversion



Concept – Predicted performance for two payload masses

Characteristic	case 1	case 2	case 3
Mass payload (kg)	200	10	10
Total Energy stored (J)	1.0e8	1.0e8	1.5e7
Isotope power (W)	1000	1000	1000
Mass Pu-238 (kg)	2.0	2.0	2.0
Mass Beryllium (kg)	55.	55.	6.07
Mass flow(kg/s)	16.6	13.36	1.07
Mass initial (kg)	1061	852	75.7
Mass propellant (kg)	580	580	25.
Mass final/mass initial	0.45	0.32	.67
Ascent burn time (s)	16.45	22.6	23
Initial Thrust (N)	20115	16157	1436
Thrust at Burnout (N)	11854	9094	511
Burn Out Vel (ms^{-1})	230	327	213
Range (km)	15.9	30.9	6.2

Hopper Summary

- **The CSNR is designing a pulse power mobile platform that can cover large areas of Mars within a few years using local in-situ resources**
- **The platform can "hop" every 5-7 days and cover 5-10 km per hop**
- **If several such platforms could be simultaneously deployed from a single launch vehicle, a surface network of science stations would be possible that provided long term assessment of meteorological conditions.**
- **The concept can be demonstrated on Earth using an electrically heated core and existing power conversion technologies for modest cost**
- **Other applications of the pulse power capability of the "thermal capacitor" concept may include satellite station keeping and burst communications**
- **The Hopper can enable samples from all over Mars to be analyzed by MSL or returned to Earth.**
- **The Mars Hopper can revolutionize planetary exploration**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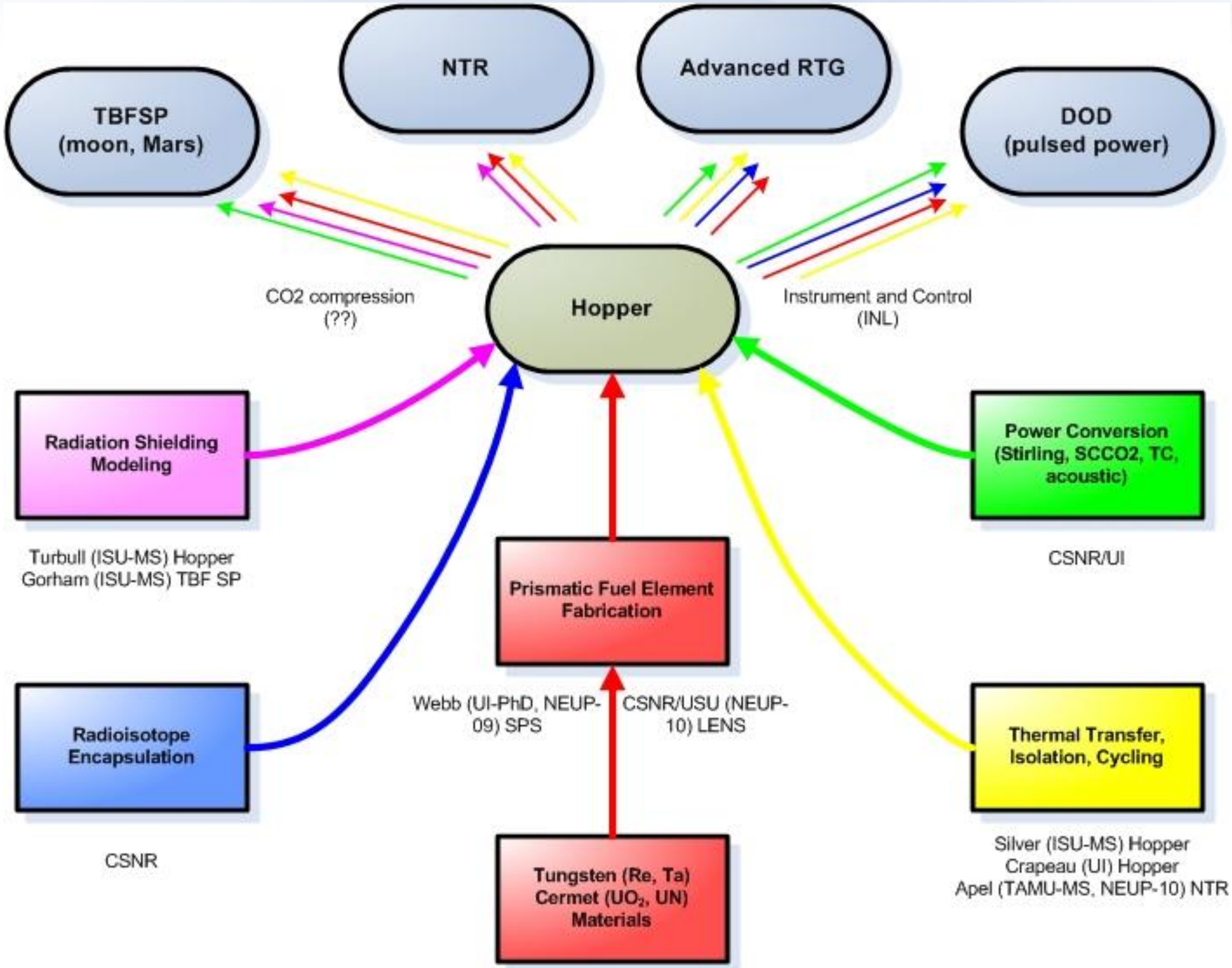


NTR
Advanced RTG
TBFSP
(moon, Mars)
DOD
(pulsed power)
CO2 compression
(??)
Hopper
Instrument and Control
(INL)
Radiation Shielding
Modeling
Power Conversion
(Stirling, SCCO2, TC,
acoustic)
Turbull (ISU-MS) Hopper
Gorham (ISU-MS) TBF SP
CSNR/UI
Prismatic Fuel Element
Fabrication
Radioisotope
Encapsulation
Webb (UI-PhD, NEUP-
09) SPS
CSNR/USU (NEUP-
10) LENS
Thermal Transfer,
Isolation, Cycling
CSNR
Tungsten (Re, Ta)
Cermet (UO_2, UN)
Materials
Silver (ISU-MS) Hopper
Crapeau (UI) Hopper
Apel (TAMU-MS, NEUP-10) NTR

NTR Development - Strategic Issues

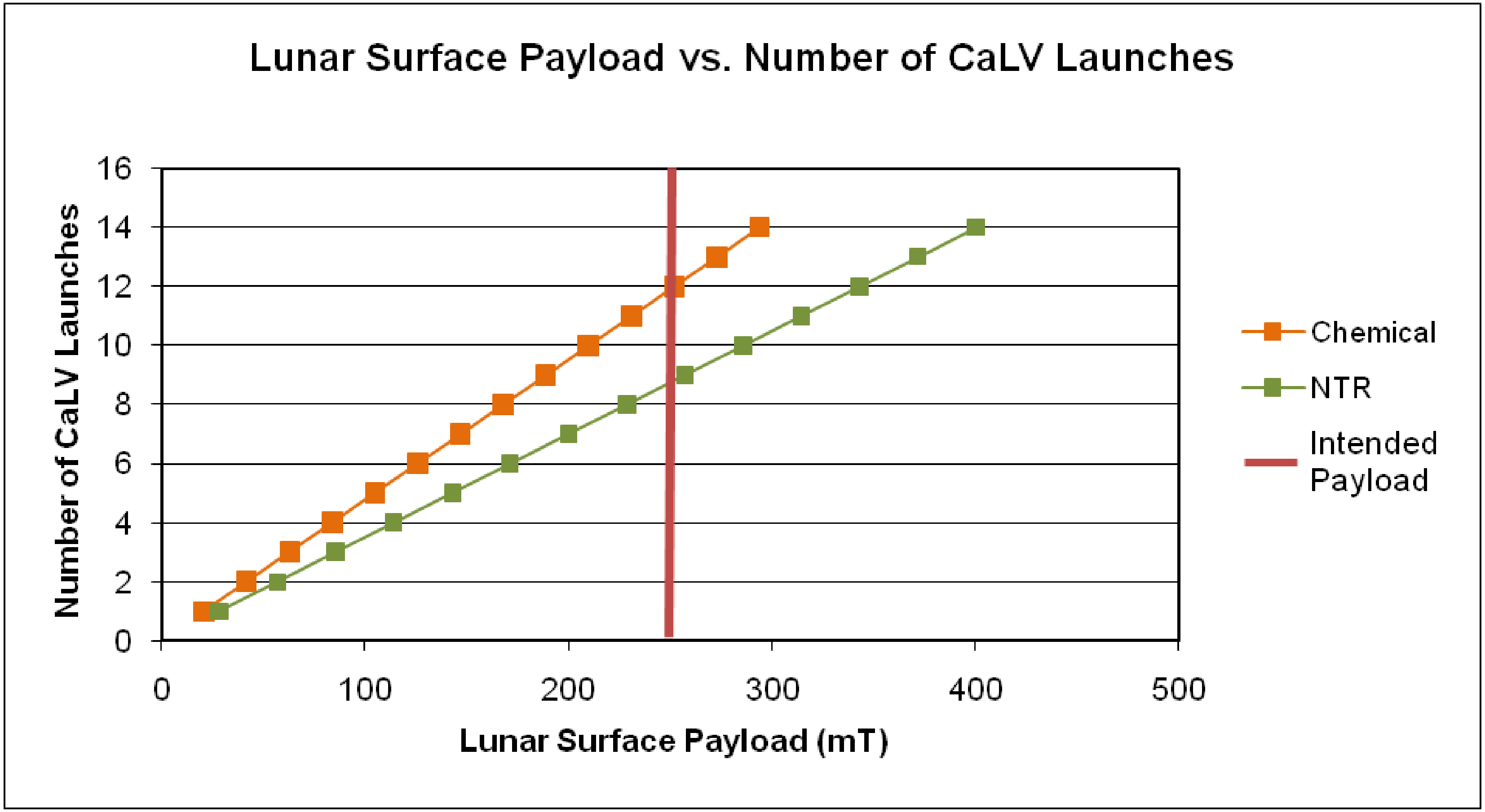
- Performance sufficiently superior to justify “perceived” risk
- Radioactivity emitted during operation
- Risk for “proliferation”
- Sub-criticality on launch abort
- Cost of development

Benefits of the NTR have been shown for several missions

- **Moon - Reduce costs of implementing a Lunar Outpost**
- **Mars - Faster missions for humans; reduced radiation exposure; lower costs for cargo; adaptability to hazards**
- **Good Asteroid - rendezvous**
- **Bad Asteroid/comet - rapid interception; destruction**
- **Outer solar system – time to “first science” within a decade for orbitor missions to outer planets and to Kuiper Belt fly-through**

In short, the NTR opens up access to the entire solar system for humans and robotic probes

NTR-Based ESAS architecture saves multiple launches of the heavy lift vehicle



Cladding Failure of Early NTR Designs implies a new fuel form is needed

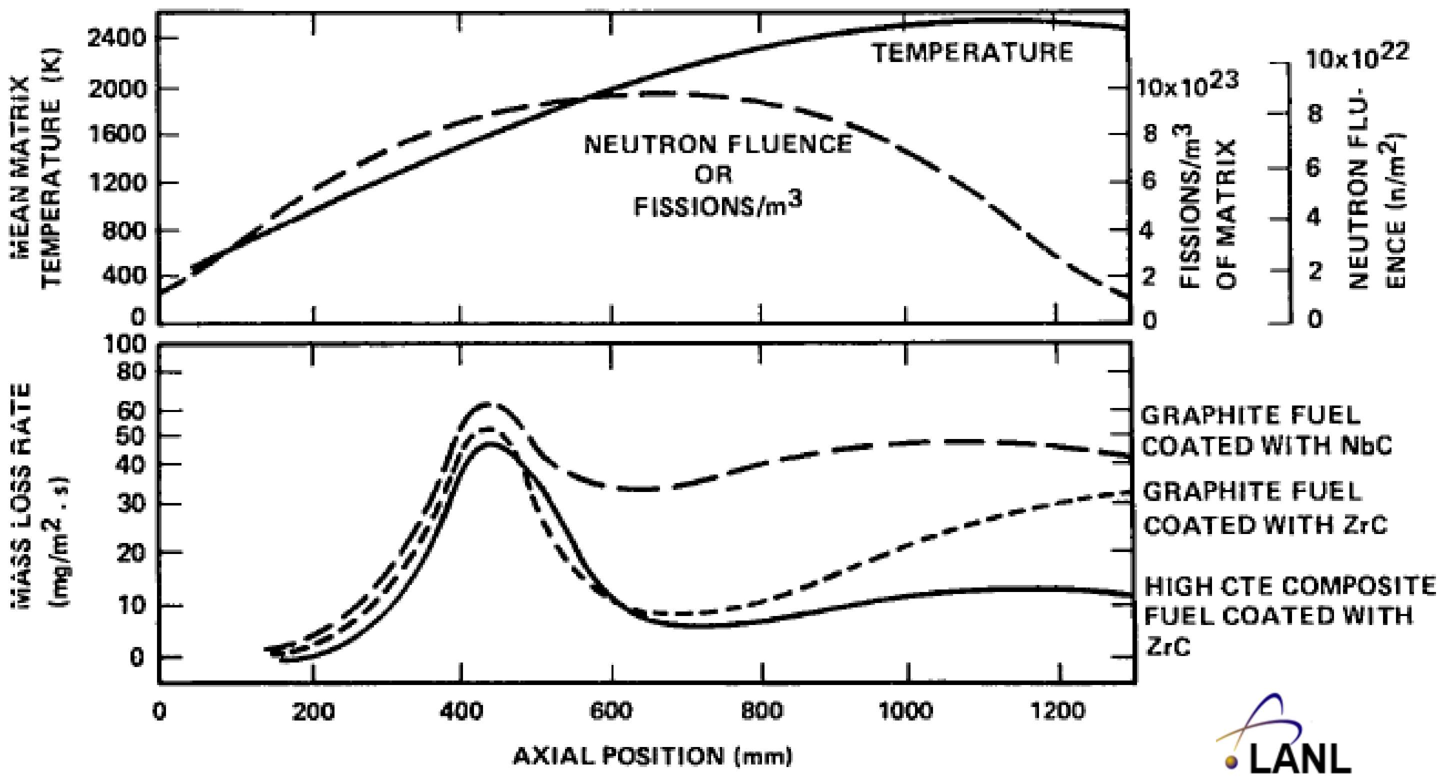


Fig. 32. Mass loss from Pewee and NF-1 fuel elements versus axial position and reactor environment. The peak in the mass loss curve is the so-called midrange corrosion. The best performance was obtained with the composite fuel coated with ZrC.

Issues - proliferation

- **Launch aborts must be considered**
- **Fast reactors offer less chance for criticality on submersion than epi-thermal systems but contain more fissile material**
- **Dispersion upon reentry is not attractive from an environmental impact perspective**
  - **Even thought he engine has no fission product inventory and is "cold"**
  - **Engine should stay intact upon reentry**
- **Dropping a few hundred kilograms of fissile material into foreign states could be considered a high risk**
  - **Could constrain launch profile**
  - **Could dictate fuel form**

Tungsten Cermet NTR remains subcritical on launch abort submersion

k is normalized to critical configuration

Configuration	k_{eff}
Basic Core Criticality	--
Boron Drums Closed	0.931
Bare Core	0.696

$\sigma_k = 0.003$

Configuration	k_{eff}
Reflectors w/ Drums Closed	--
Freshwater	0.977
Seawater*	0.976
Dry Sand	0.985
Fused Silica (Dry, 5-m)	0.995
Wet (Freshwater) Sand	0.986
Wet (Seawater) Sand*	0.983

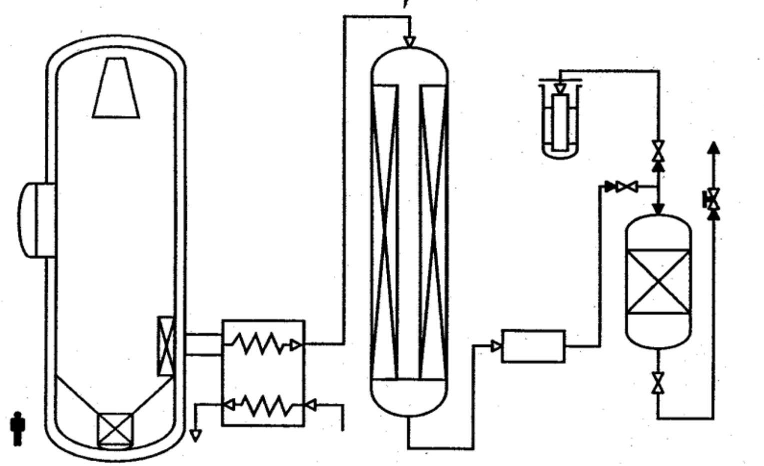
Configuration	k_{eff}
Without Reflectors	--
Freshwater	0.955
Seawater*	0.926
Dry Sand	0.980
Fused Silica (Dry, 5-m)	1.065
Wet (Freshwater) Sand	1.000
Wet (Seawater) Sand*	0.985

* Only scenarios resulting in submersion in seawater and wet sand are required for criticality accidents.

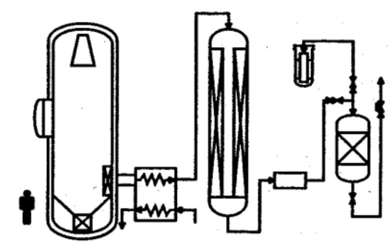
Cost of Development -- NTR Exhaust Treatment System (ETS) Size Scaling with Thrust Level

NOTE: Size of the ETS scales with hydrogen exhaust gas throughput from the engine. Small engines can be tested in the Contained Test Facility (CTF) at substantially lower cost than the large engines developed during the Rover / NERVA programs. Detailed cost estimates being prepared by INL and DOE for NASA GRC.

**~$ 0.5-1.0B*
(SEI -- 1990)**

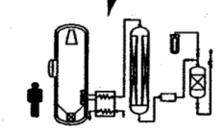


80 klb_f



40 klb_f

Small BNTR can use existing CTF at INL



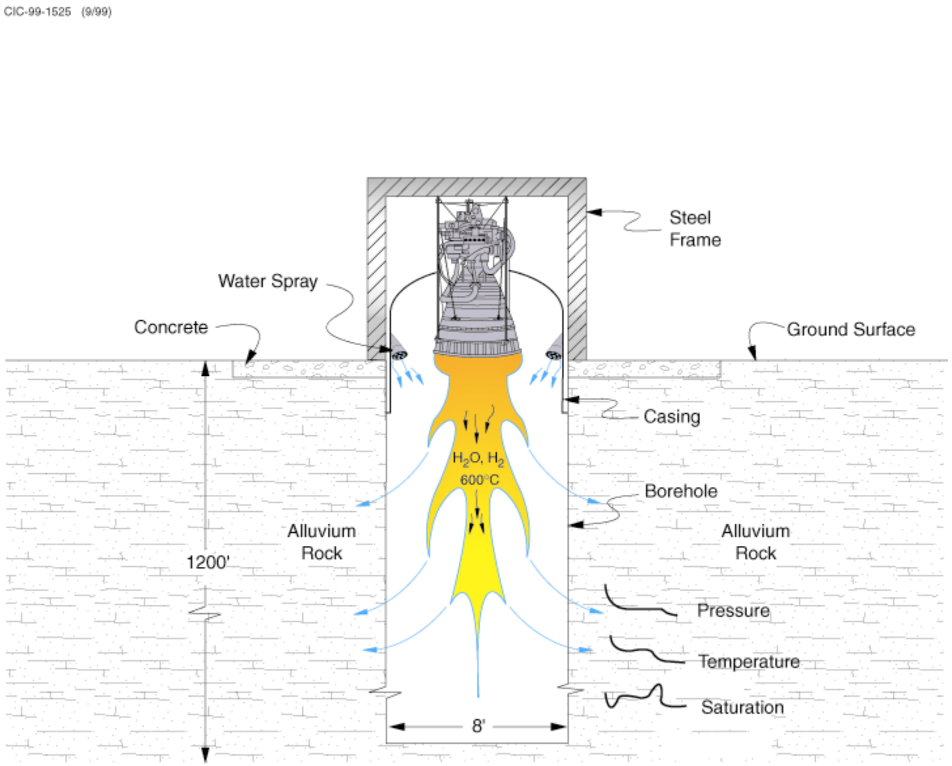
10-15 klb_f

*** NOTE: Not shown above is the large containment structure that would enclose the engine & ETS and that is included in the cost number**

Source: Idaho National Laboratory (INL)

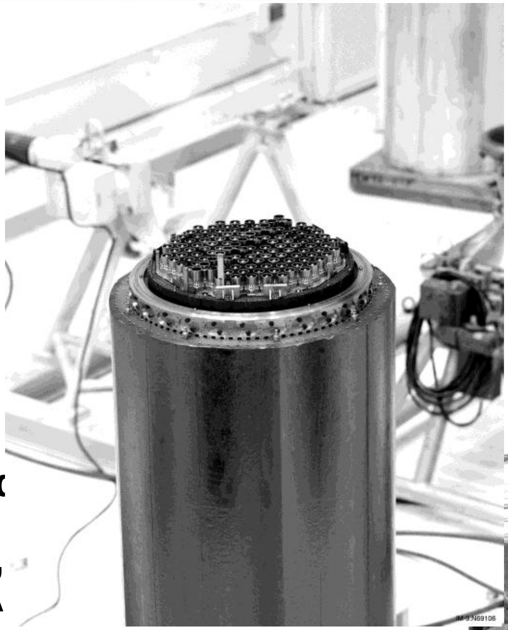
Cost fo Development- Sub-surface Active Filtering of Exhaust (SAFE) may enable much cheaper ground tests

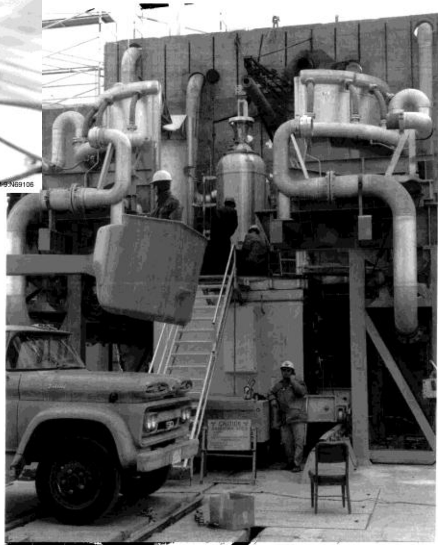
- **Nuclear furnace proved ability to scrub exhaust**
- **Scaling to full power engines implies a costly facility**
- **SAFE offers one cheaper option if proven feasible**
- **If fuel doesn't leak fission products, then test facility is only for off-nominal conditions**



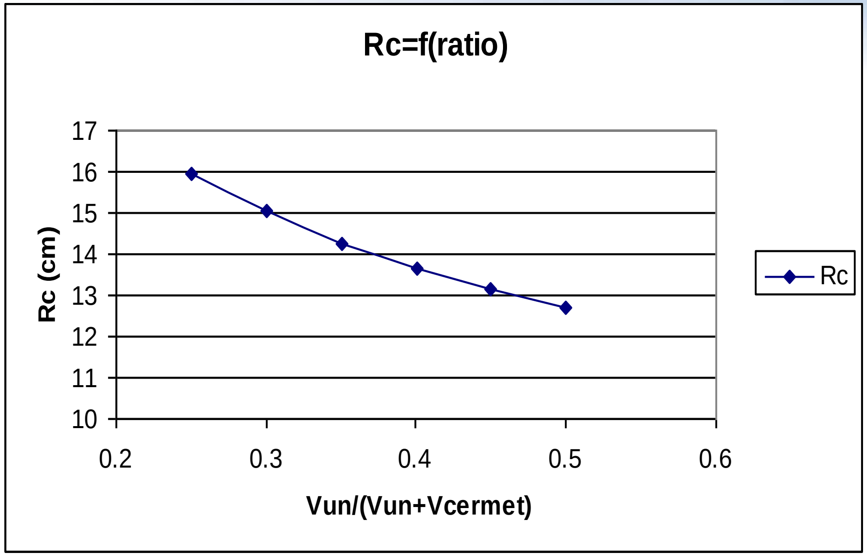
Pewee was a lessons learned test of a small NTR

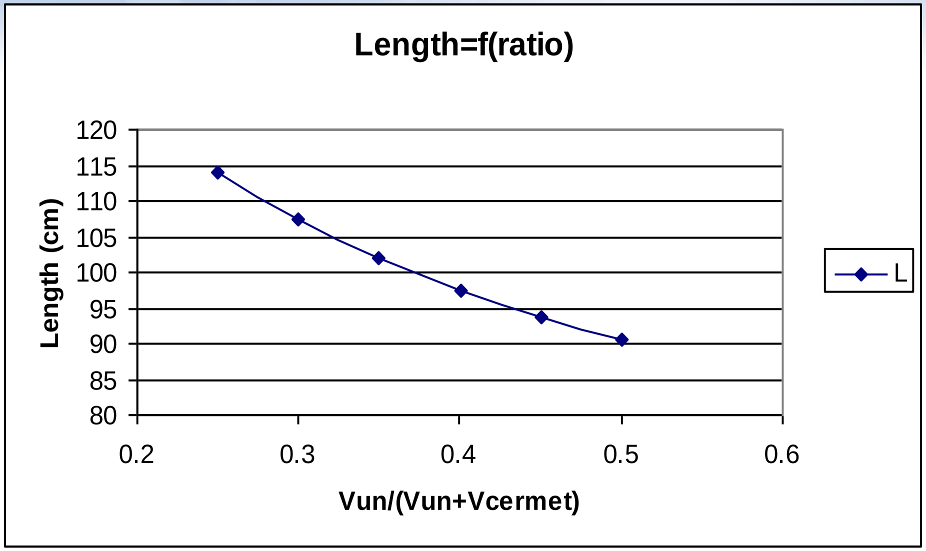
- The goal was to produce a reactor with 500 MW thermal power (corresponding to around 25,000 lbsf of thrust (estimated) and a thrust to weight ratio greater than 4).
- A major design change was the incorporation of lithium-hydride into the tie-tubes. This softened the neutron spectrum somewhat and enabled a smaller mass core.
- The ratio of fuel elements to tie-tubes was decreased from the 6:1 value in the Phoebus engines to 3:1.
- The chamber pressure in the Pewee was designed to be around 800 psia. This enabled a higher power density of around 1.4 MW per fuel element, 50% greater than the power density in the NERVA engine.
- The Pewee I was tested at the Nuclear Rocket Development Station at the Nevada Test Site in December of 1968.
- The reactor operated at full power for 40 minutes at 503 MW with an estimated specific impulse of 845 s. Estimated thrust would have been just over 27,000 lbf.
- Total engine mass was 2570 kg indicating a thrust to weight potential of 4.8. Maximum power density was 5200 MW/m3.

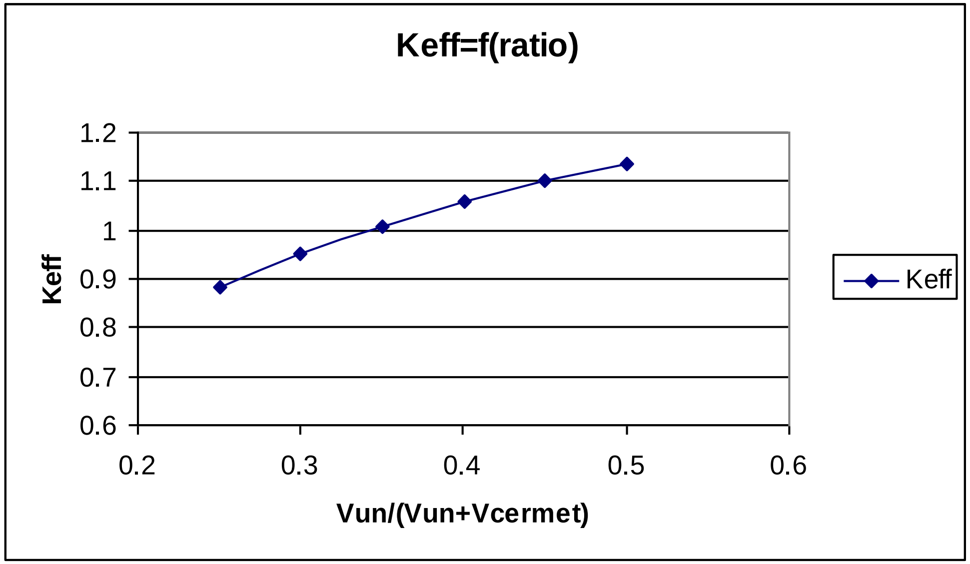




Tungsten fueled Pewee is critical







Reactor Fuels Development -- can the country afford more than one

- **The requirements of the NTR place rigorous constraints on the fuel**
- **While "normal" power reactor fuel can't work in the NTR, BUT the NTR fuel could work in a power reactor**
- **Development of one fuel form to serve both power and propulsion could ultimately be a cost savings for the program**

Comparison of size and shield masses for NASA's Fission Surface Power (FSP) reactor and a Tungsten Based FSP

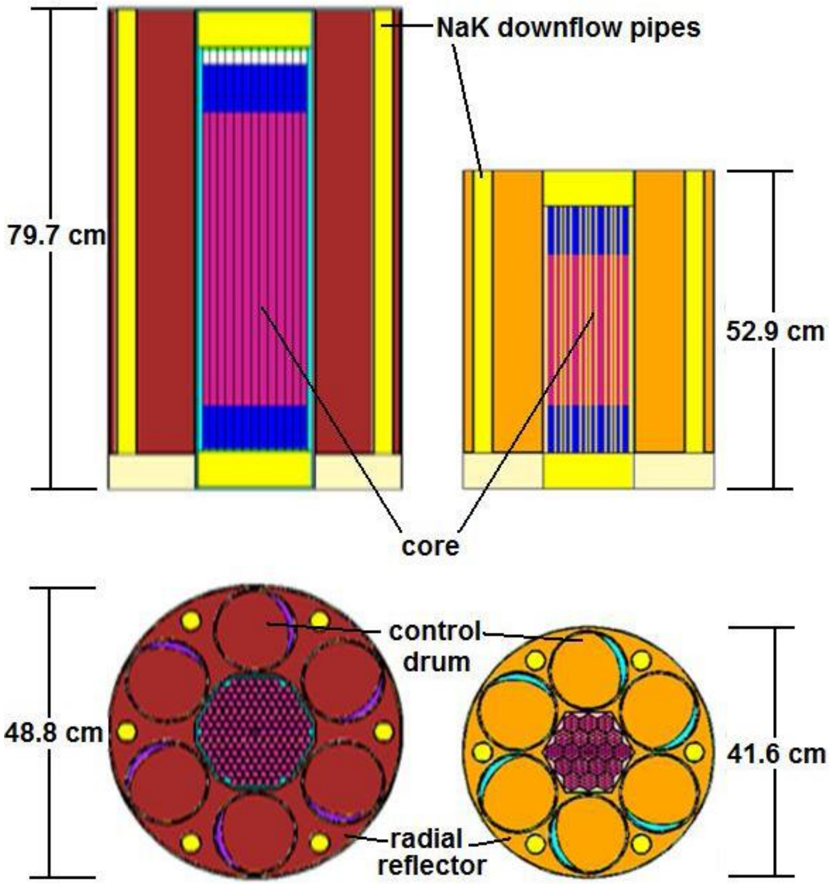


Table 1. Shield Parameters for AFSP and TBFSP.

Parameter	AFSP	TBFSP	Δ
outer diameter (cm)	48.8	41.7	7.1
height (cm)	79.7	52.9	26.8
reactor mass (kg)	~352	~225	127.0
BH2O Shield			
outer diameter (cm)	190.2	183.1	7.1
height (cm)	196.8	170.1	26.7
shield mass (kg)	6712.5	5510.3	1202.2
total mass (kg)	7064.5	5735.3	1329.2
Trilayer Shield			
outer diameter (cm)	185.2	179.3	5.9
height (cm)	197.8	175.5	22.3
shield mass (kg)	6880.0	5286.6	1593.4
total mass (kg)	7232.0	5511.6	1720.4

Courtesy CSNR 2009 Summer Fellows

Mars Sample Return Mission Architecture Utilizing a Nuclear Thermal Rocket

CSNR 2010 Summer Fellows

Ross Allen, Regal Ferrulli, Brian Manning

Center for Space Nuclear Research

September 9th, 2010

Mars Sample Return Mission Architecture and Preliminary Nuclear Thermal Rocket Spacecraft Design

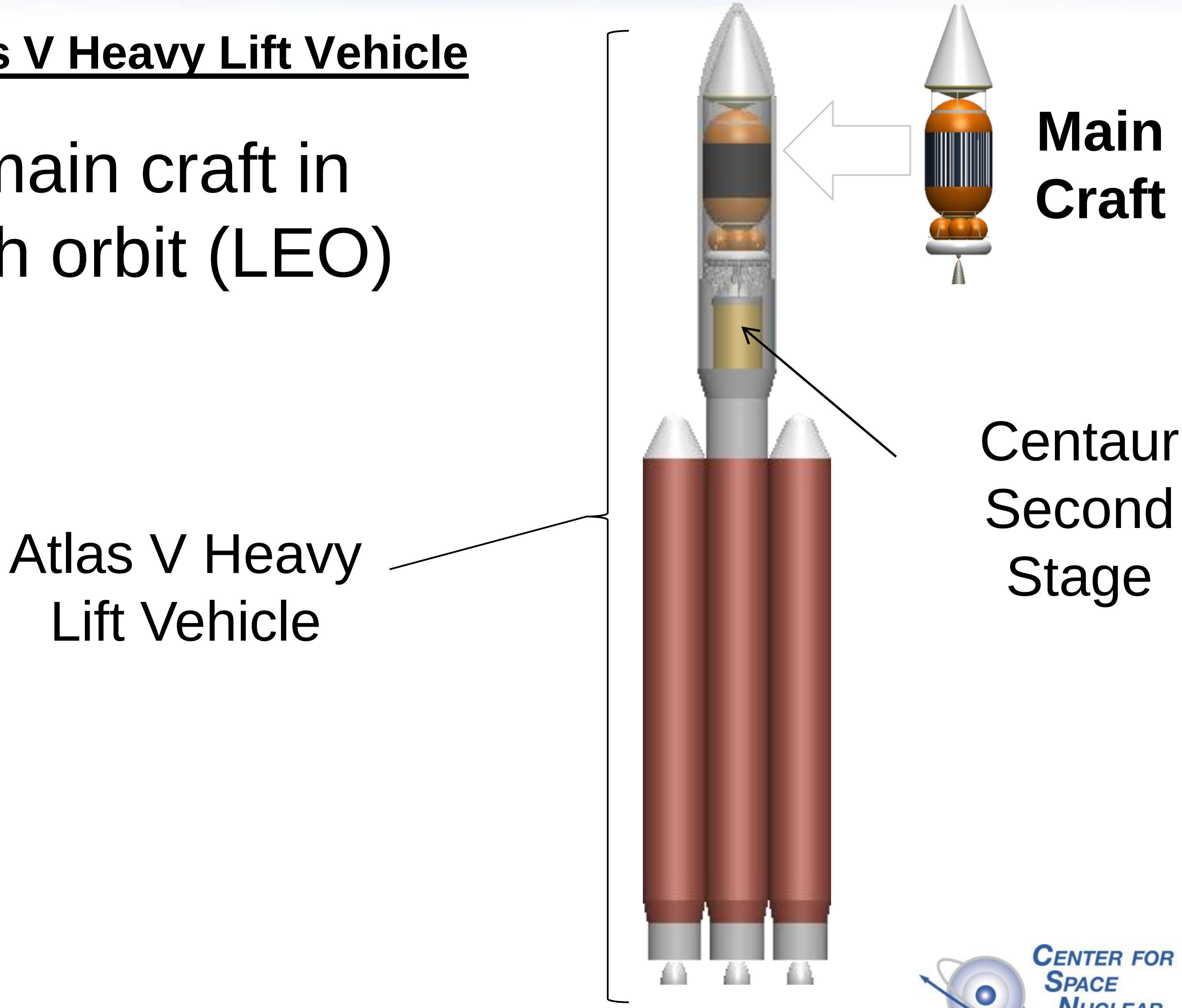
Basic Mission Design:

- **Place entire craft in LEO with ONE Atlas V Heavy**
- **Conjunction class transfer to Mars with H_2**
- **Mars arrival**
  - Burn with H_2 and enter highly elliptical orbit
  - Aerobrake return rocket/tank
- **Descend lander vehicle with NH_3**
- **500 day stay on Mars**
- **Collect 100 kg of Martian samples from hoppers**
- **Ascend with CO_2 to 200 km orbit**
- **Rendezvous with main vehicle and transfer samples**
- **Transfer to Earth with H_2**
- **Jettison sample entry capsule to Earth**

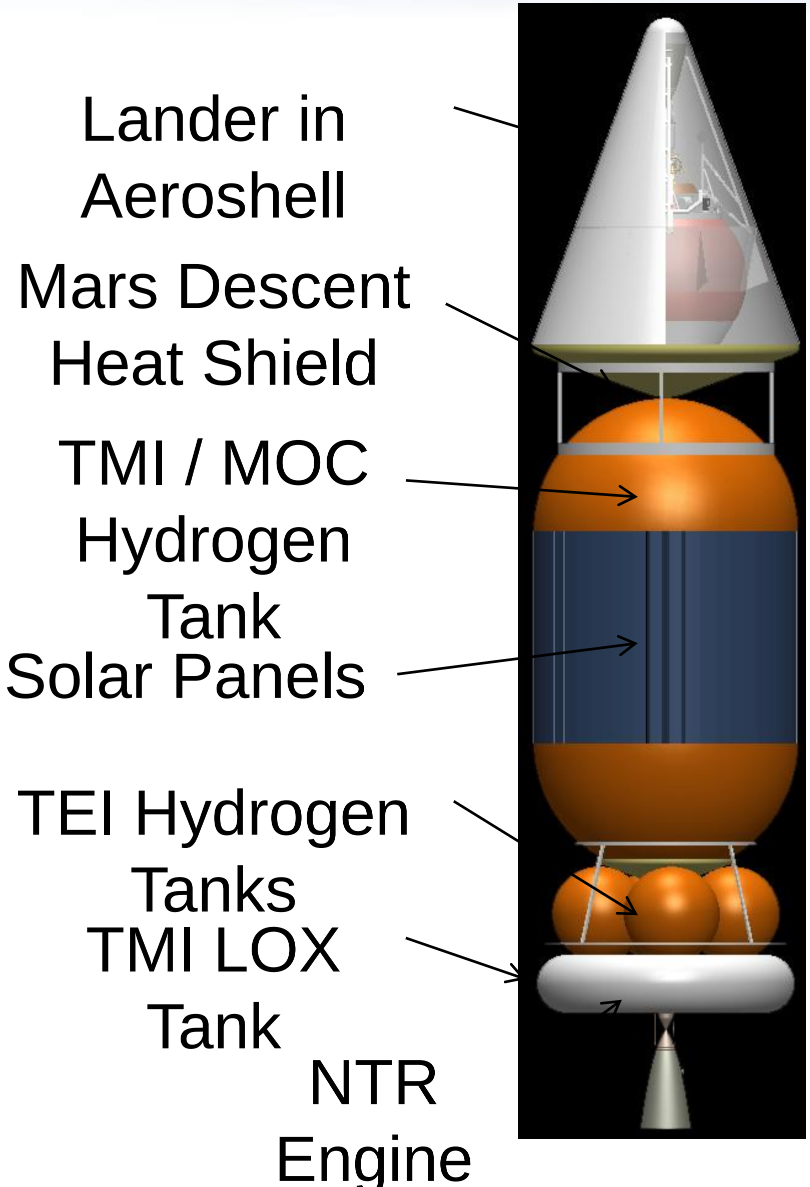
Spacecraft Configuration

Atlas V Heavy Lift Vehicle

- Places main craft in low Earth orbit (LEO)

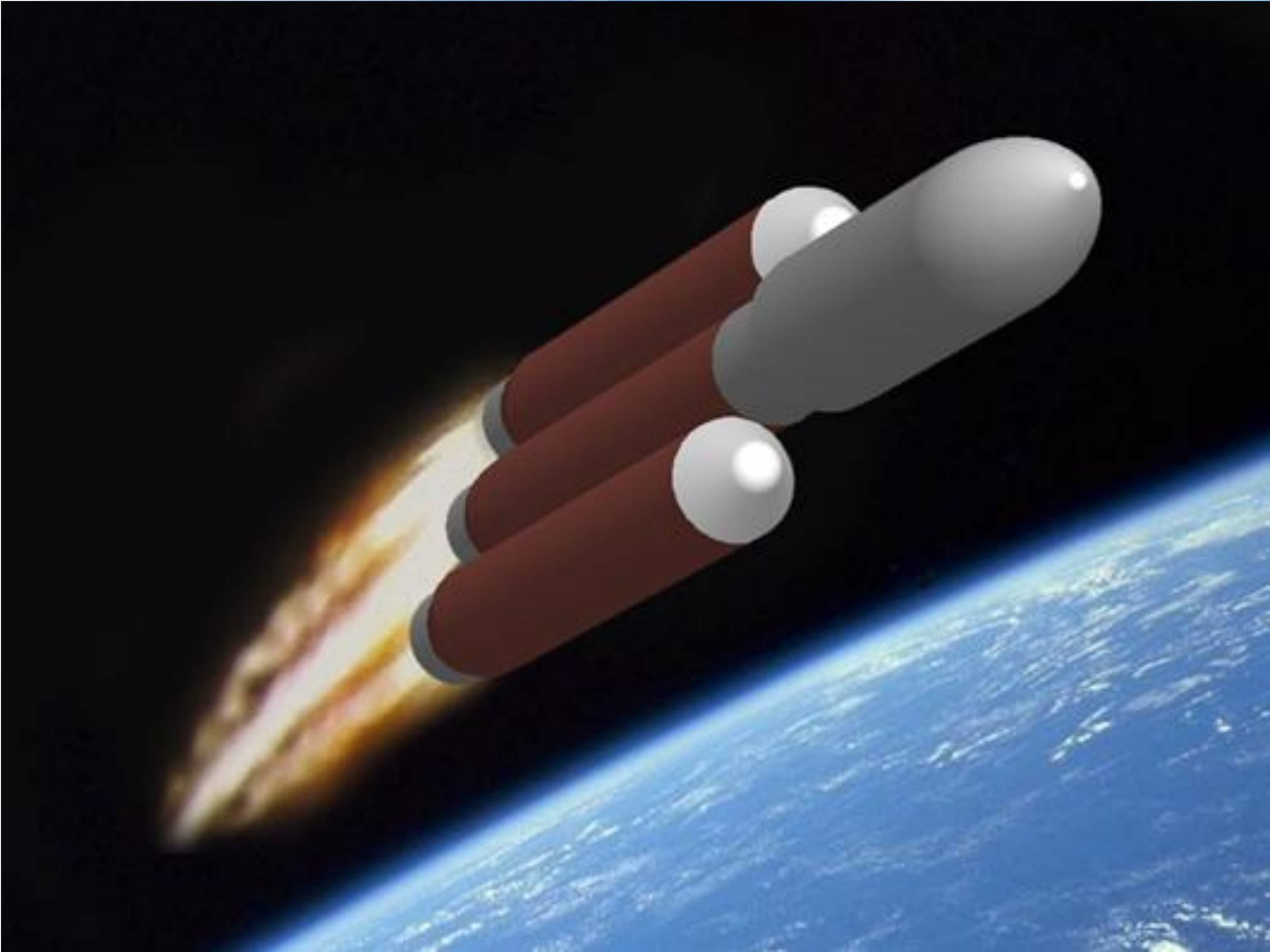


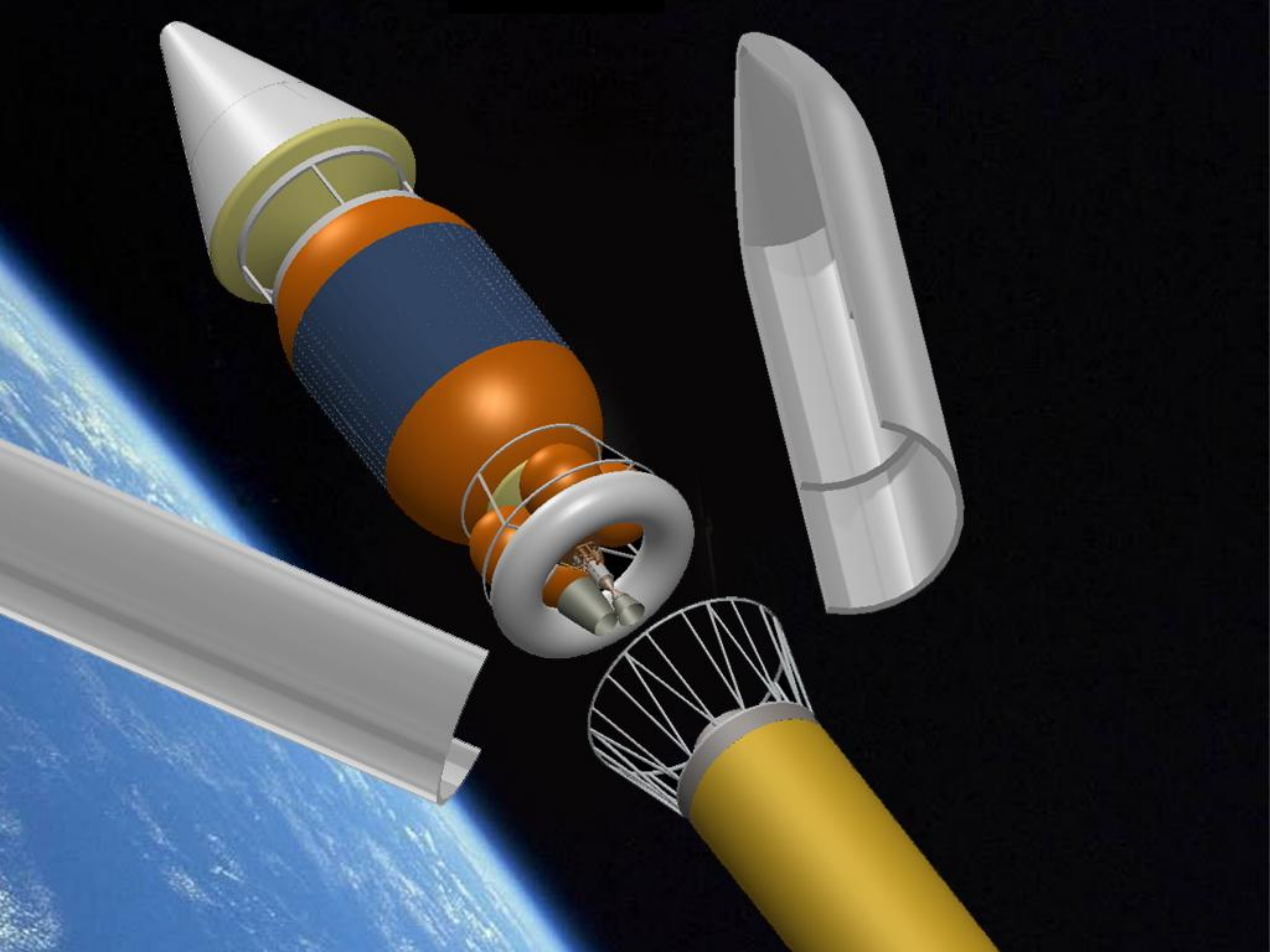
Spacecraft Configuration

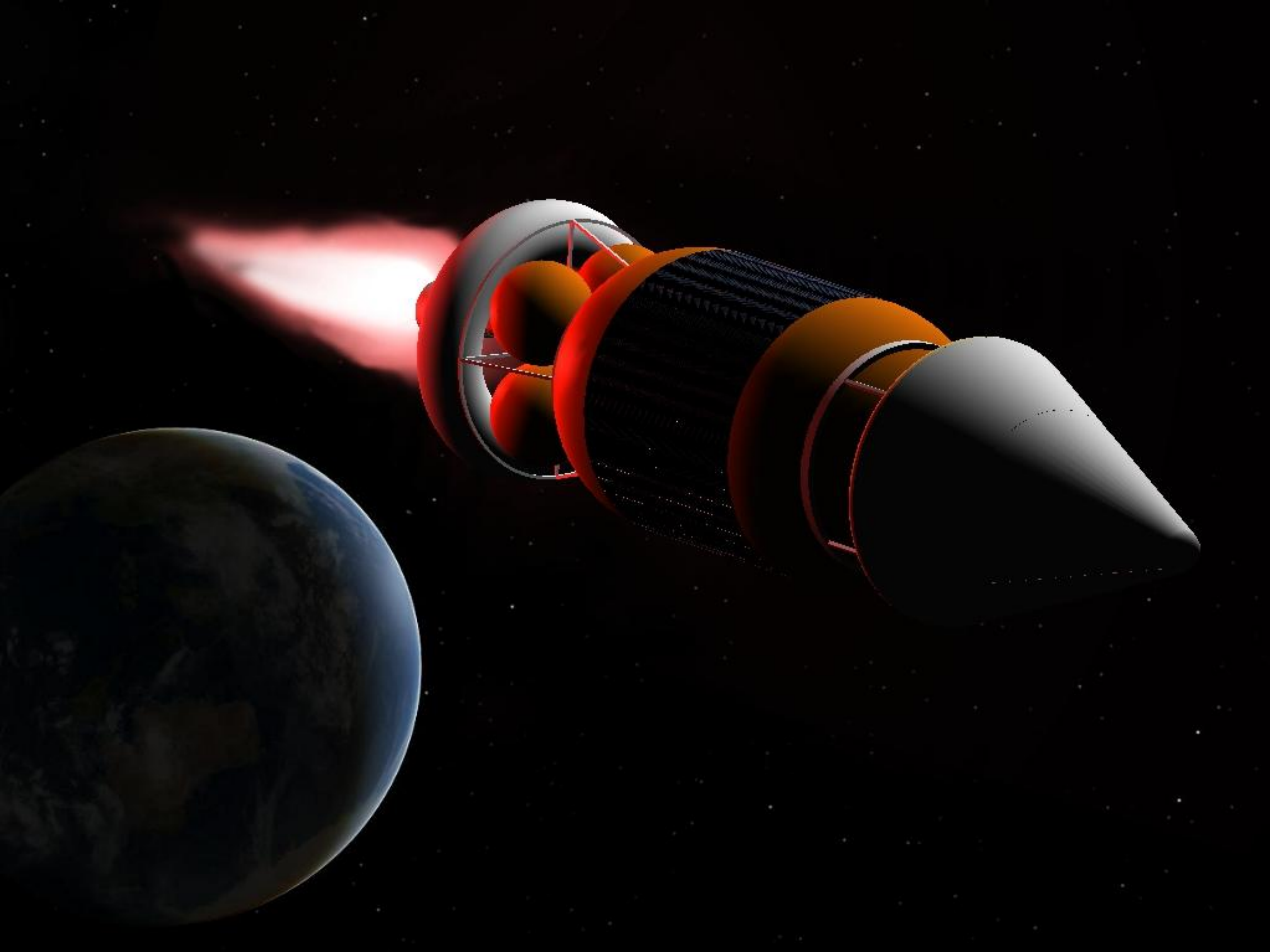


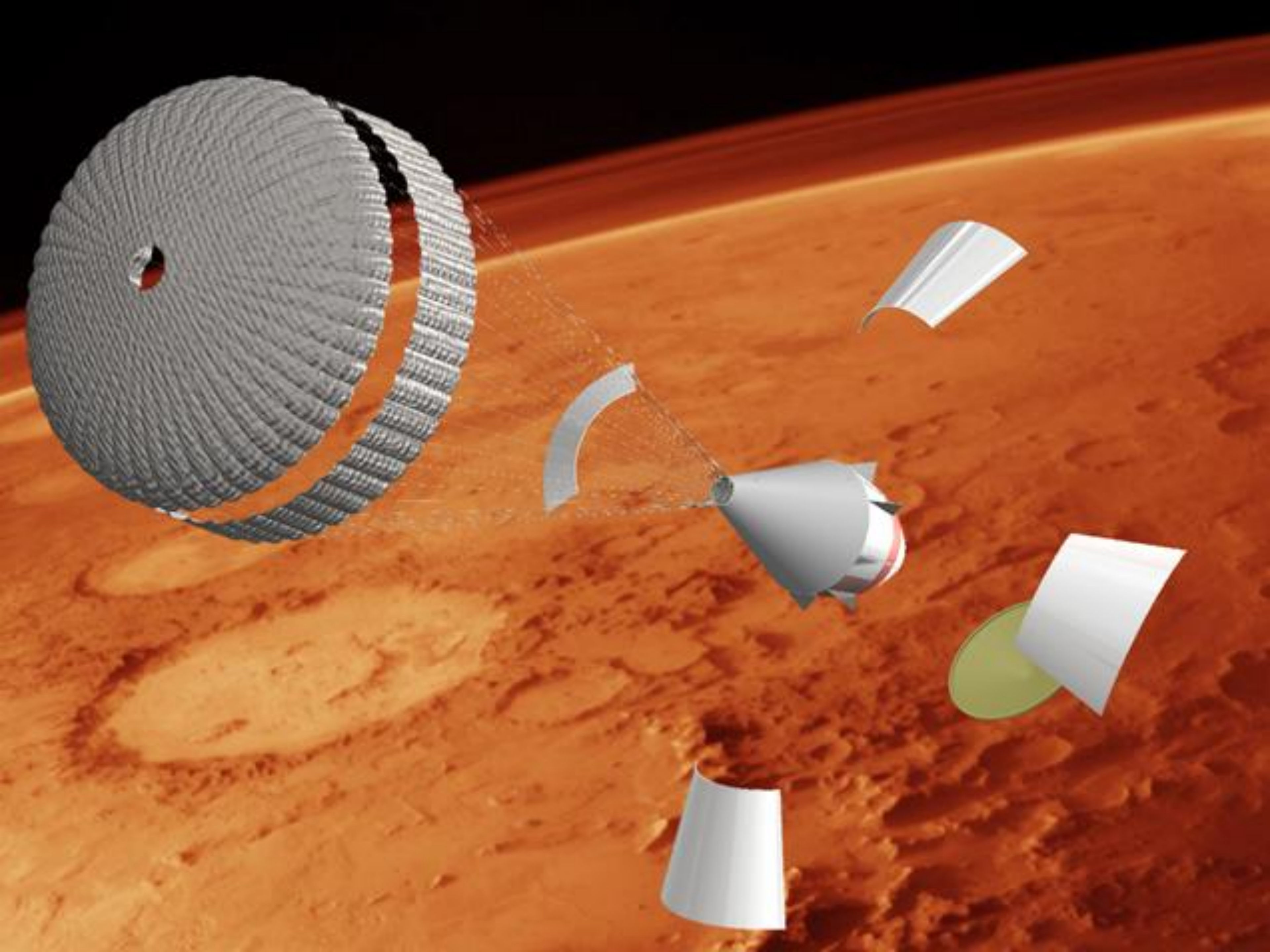
Main Craft

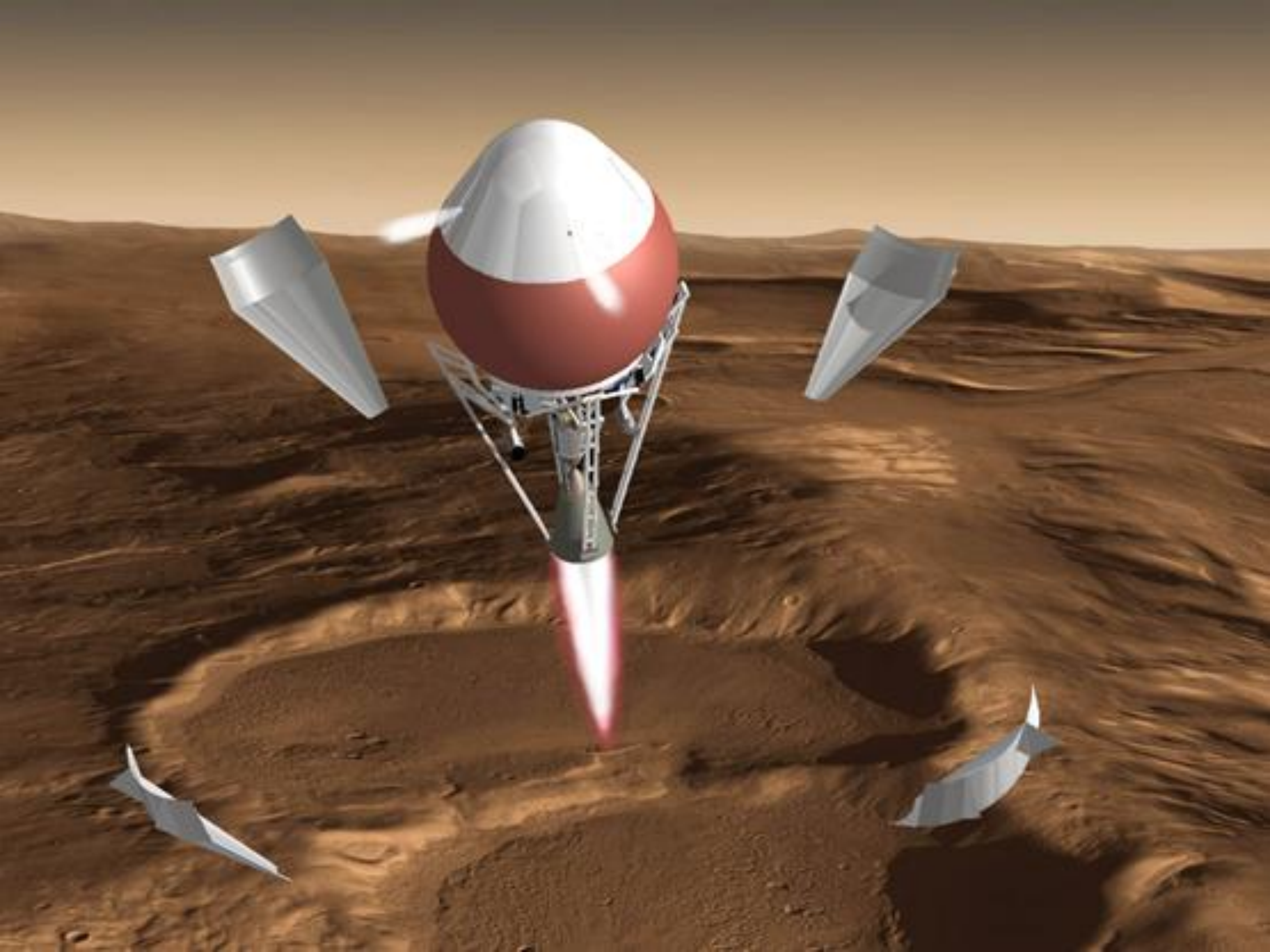
- Transports to Mars
- Orbits Mars during collection
- Rendezvous with ascent vehicle
- Transits back to Earth

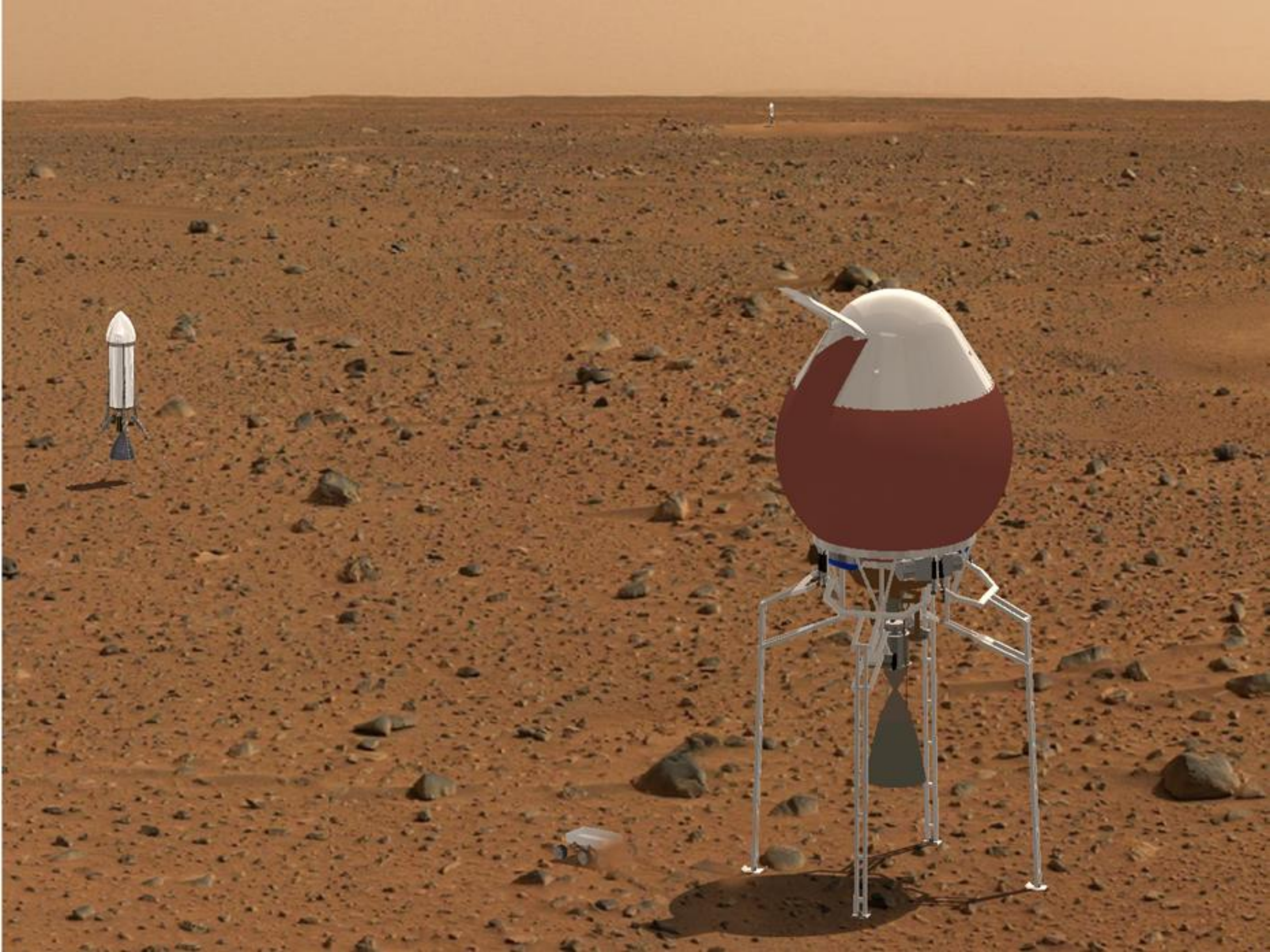


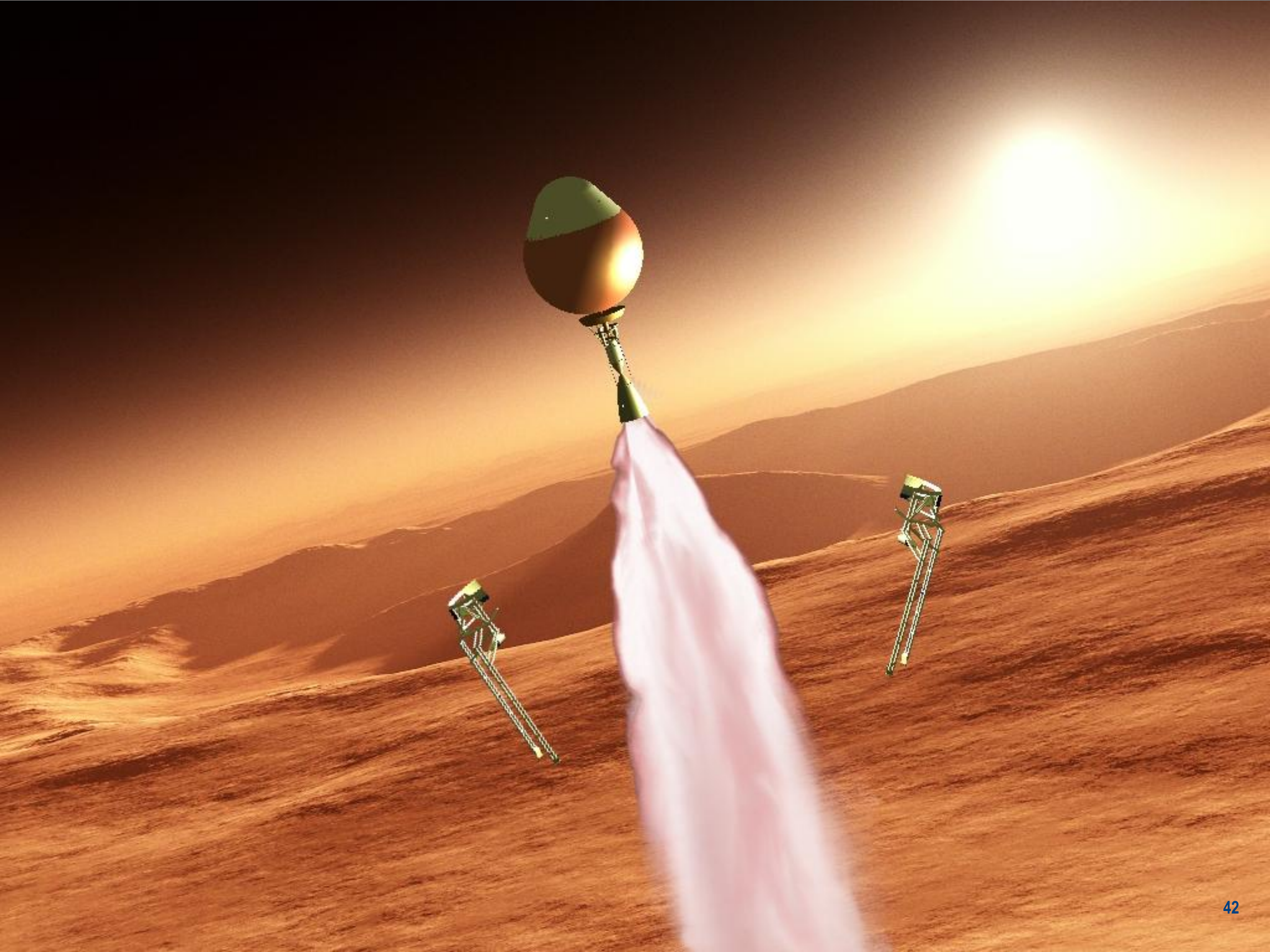


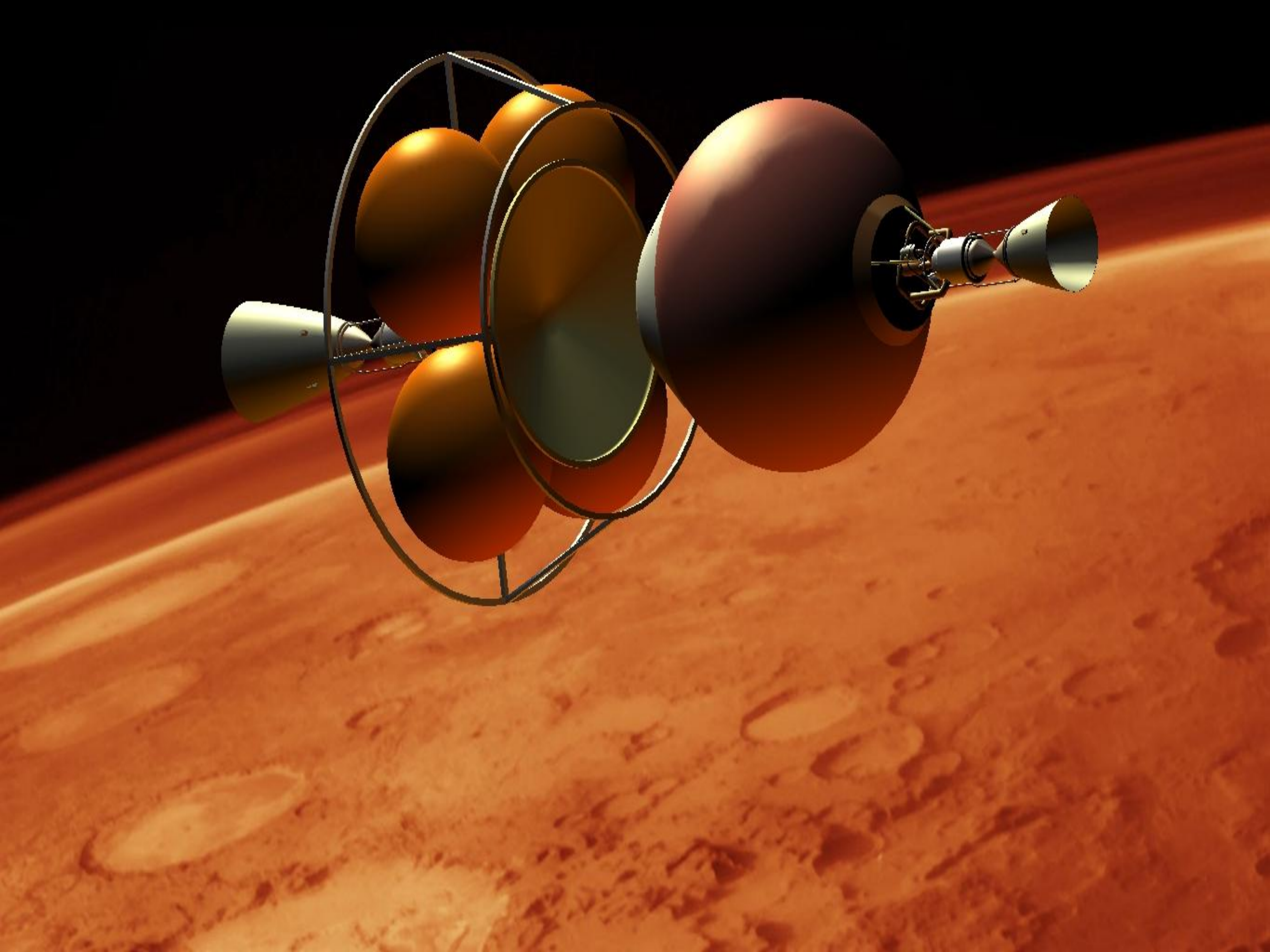


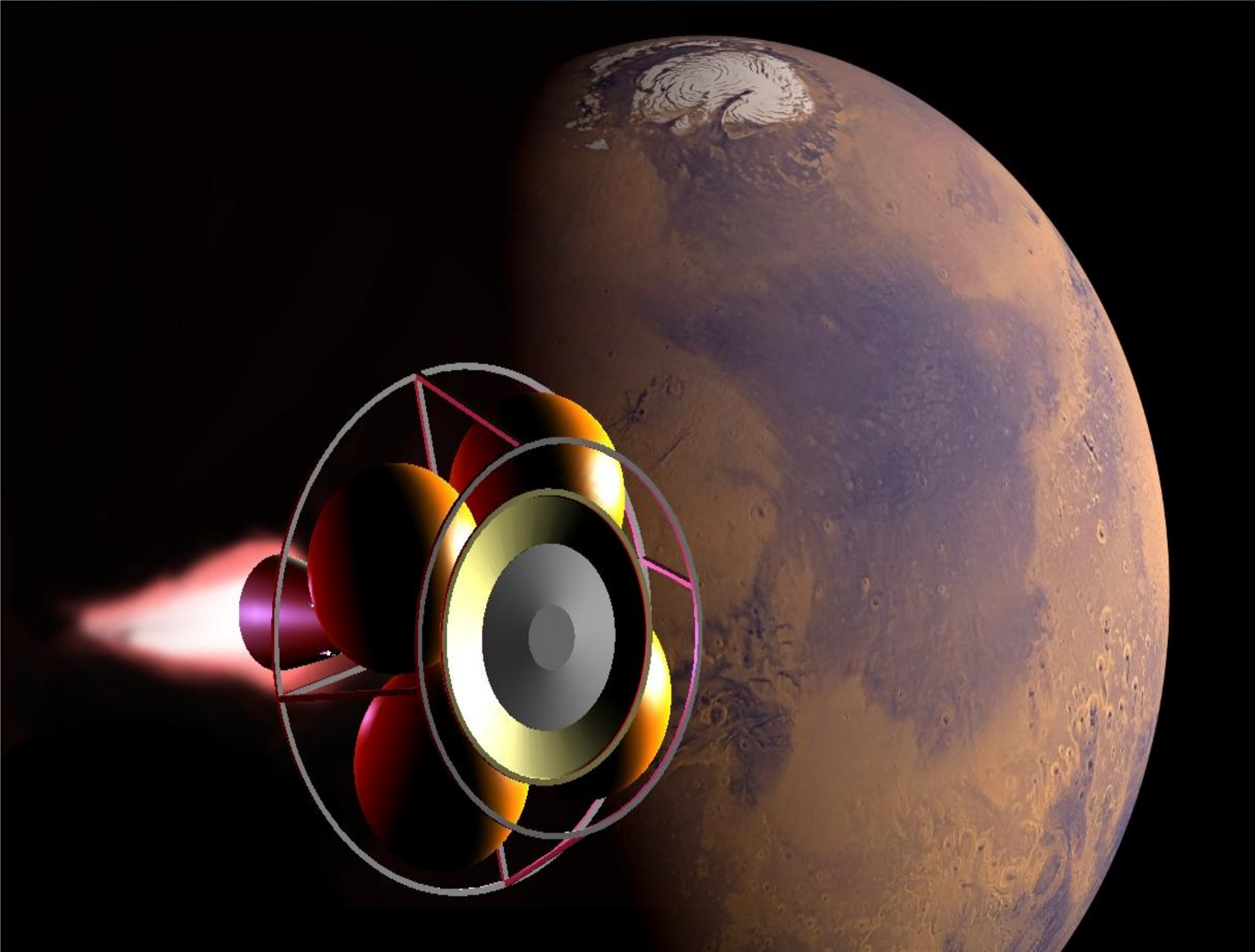




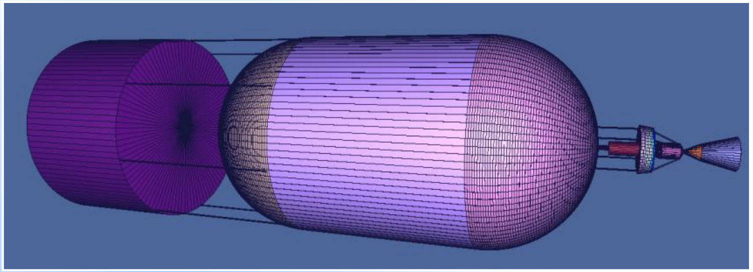








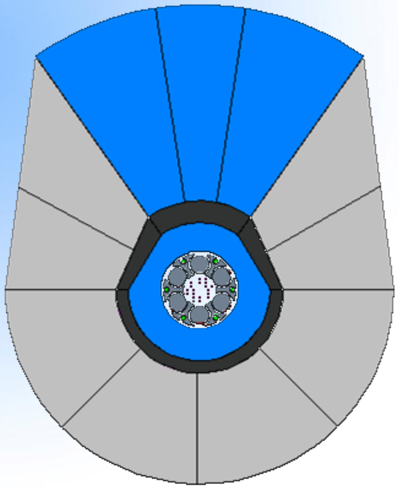
CSNR Summer Fellowships program has proven the ability to attract top students



- **5 years running**
- **Nationwide search**
- **Accept applications for 2 months**
- **Unique research projects each year**
- **Goals**
  - Provide Student Fellows an in-depth understanding of nuclear reactor and radioisotope power and heating technologies applied to space exploration
  - Gain experience using complex computer codes that will be applicable to modeling nuclear systems
  - Speaking and writing experience (weekly presentations by students)
  - Exposure to INL and Idaho Falls
  - Produce sufficient information for production of unsolicited proposals to federal agencies
- **Provide pool to fill "Next Degree" opportunities**
  - Identify good fits to INL and not-so-good fits

2010 CSNR Summer Fellowships

- **Funded by a combination of**
  - NASA - 1 team
  - INL LDRD program – 3 teams
- **158 applications – due to USRA broadcast to members**
- **Accepted 20 Fellows represent 14 states and 17 universities**
- **5 MS, 12 seniors, 1 undergraduate, 1 USAF cadet senior, 1 Rocky Mt. Space grant senior**
- **Disciplines**
  - 3 Nuclear eng.,
  - 7 mechanical eng.,
  - 3 physics,
  - 7 aerospace eng.,



- **Working on “challenging” topics attracts the students**
  - Mobile lunar base, nuclear rockets, decoupled fast reactors, isotope powered UAVs and UUVs, “smart” shields, comet interceptors, Mars Hopper

Idaho National Laboratory

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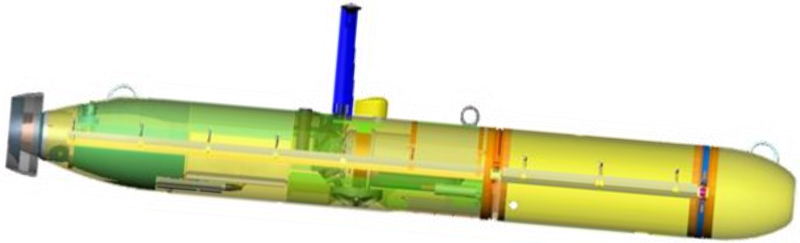
Next Degree (NxD) Program Objectives

- **Build technical workforce in the CSNR and provide a feedstream into INL**
  - Difficult to develop projects in CSNR without feasibility studies
  - Hard to do feasibility studies using INL staff without funding
  - Shortage of NE graduates- getting worse
  - Students are tempted to leave early for a paycheck
- **Desire is to attract top quality students from around the country to INL/CSNR by engaging them in space exploration projects**
  - Many students do not automatically see INL and Idaho as a premier research location
- **NxD students work ½ time at industry competitive salary on CSNR or INL project and ½ time on their next degree**
  - Able to retain school affiliation or enroll in Idaho Universities
- **Number of NxD students increased to 9 in FY09**
  - 4 PhD and 5 MS



Summary

- The CSNR is developing new Universal Encapsulation technology that is applicable to several nuclear systems
- The Mars Hopper concept can revolutionize planetary exploration and provide dramatically greater science per launch dollar
- The Hopper requires several capabilities that directly overlap the ability to design and test a NTR
- The CSNR has performed several mission studies that show the benefit of the NTR and the tungsten-cermet fuel